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Manuscript title: A multi-variable study of factors affecting the complex resistivity of conductive mortar

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Abstract

Twenty four mortar mixes have been tested to assess the effects mix design factors on complex electrical resistivity. Of these mixes, 6 were conventional and 18 were conductive mixes containing varying quantities of either graphite or carbon fibre powder additions, which have been shown in previous studies to reduce the resistivity of cementitous materials. Complex resistance measurements from 20Hz-10MHz taken between 7 and 35 days after casting were analysed. Comparisons were made between the effects on complex resistivity of varying quantities of additions, water/cement ratio, and grit/sand ratio. In conventional mixes w/c was found to have more significance for complex resistance than g/s. Conductive additions were found to reduce complex resistivity magnitude as well as the influence of other mix factors. This novel and comprehensive comparison of the effects of three elements of mix design on complex resistance will be of use to anyone wishing to produce mortars or concrete for use in self-heating, self-sensing, or electrical property imaging contexts.

Keywords: Cement/cementitious materials; Composite materials; Electrical properties

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1. Introduction

In some applications, it may be advantageous or necessary to design concrete with the intent of controlling its electrical properties. The resistivity of conventional concrete varies significantly with its saturation level, but for dry concrete a value of $10^6\ \Omega \cdot \mathrm{m}$ is typical (Hornbostel *et al*., 2013). This compares to metals which generally have resistivity in the order of 10^{-7} or $10^{-8}\ \Omega \cdot \mathrm{m}$. Therefore reducing the resistivity is likely to be the more common usage case for efforts to control the electrical properties of concrete.

One example of an application of conductive concrete is self-heating concrete, as described by Tumidajski *et al*. (2003), Hou *et al*. (2010), Maleki *et al*. (2017) and others. In this application, the conductive concrete dissipates energy by heating when a current flows through it. The principal use for this is in de-icing of pavement or road surfaces.

Conductive concrete has also been studied as a potential material for electromagnetic shielding by Ogunsola *et al*. (2009) and Khalid *et al*. (2017). In both studies the resistivity of the concrete was decreased by the addition of conductive materials. Zhang *et al*. (2017) have demonstrated the possibility of using conductive concrete to produce grounding electrodes for use in components of power networks.

Another major application for conductive concrete is for assessment of damage via structural health monitoring – so-called “Self-sensing” concrete. Ding *et al*. (2015) measured the change in resistivity of conductive concrete as a method for detecting damage caused by freeze/thaw cycles, and found that the relationship between resistivity change and number of cycles was quite consistent. Their results also show that conductive additions may have desirable effects on the mechanical properties ofthe concrete. Chu and Chen (2016) compared the relationship between resistivity versus strain for conductive concrete during cyclic loading, showing that damage can be detected by observing changes to the resistivity. Another potential application is the production of concrete that can be more easily imaged using electrical property measurement techniques similar to those described by Ammari *et al*. (2014) and Hallaji *et al*. (2015). This has been explored by Huang *et al*. (2016). The list of substances that may be useful as additions given by Xie *et al*. (1995) is relatively comprehensive. More recently other carbonaceous materials have been considered, including graphite powder, carbon nanofibres and carbon nanotubes (Gomis *et al*., 2015) and carbon fibre reinforced polymer (CFRP) (Maleki *et al*., 2017). From the results presented by Gomis *et al*. graphite powder and carbon fibre powder have varying effects on the resistivity of cement paste depending on the moisture content of the mix, but variations in w/c in that study make it difficult to isolate the effects of the carbonaceous materials. In the same study the nanofibres and nanotubes had a profound effect with the nanotubes reducing resistance in their dry test specimens by four orders of magnitude compared to the same weight percentage of carbon fibre powder, though again the w/c ratio was not held constant.

Hou *et al*. (2007) investigated the DC resistance of concrete with 5-10mm long carbon fibres as conductive additions, finding that for concretes with a constant dosage of 0.73% by mass of carbon fibre, increasing the content of coarse aggregate decreased resistance. Chen *et al*. (2017) also used carbon fibre powder combined with graphite powder, with several different combinations of the two materials up to 7.75% by mass of cement showing around 1000 to

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1150 $\Omega \cdot cm$ before any cyclic loading. This was reduced by the gradual application of a compressive stress up to 30MPa, and then consistently reduced by around 10% compared to the original value after returning to the no-load state. This represented around an order of magnitude decrease in resistivity as compared to dry conventional concrete.

Gomis *et al*. found that with 5% by mass of carbon nanotubes, the DC resistivity of the concrete mix was $0.23\ \Omega \cdot m$, and for the same quantity of carbon nanofibres $7.45\ \Omega \cdot m$. This is a particularly low value for a conductive concrete, but cannot be used to compare the two materials directly as other mix parameters were also varied. They also found that resistivity for the two concrete mixes were not significantly affected by moisture content, compared to the same weight percentage of carbon fibre powder and graphite powder. This suggests that the nanotubes and nanofibres were better distributed in the concrete matrix, and conduction paths were not reliant on the cement.

Steel fibres may be vulnerable to corrosion in the same way that concrete reinforcement is, which would affect their electrical properties and as such they are not preferred in this application. Carbon nanotubes have a profound effect on resistivity according to Gomis *et al*. but due to their present cost it is unlikely that they will be adopted for use in industrial contexts in the short to medium term. Therefore, graphite and carbon fibre powders were selected for testing in this research.
The purpose of this work was to assess the relative effects of the water-to-cement ratio (w/c), fineness of the fine aggregate and weight percentage of carbonaceous materials (WPCM) on the resistivity of several mortar mixes. Mortar has been used since itprovides the dominant conduction path in concrete, particularly at lower frequencies. In each mix, two of these variables were held constant while the other was varied. Avoiding coarse aggregates eliminated the possibility of variability caused by the distribution of the aggregates, at the cost of some direct applicability to concrete. However, the data obtained remains useful in designing conductive concretes.

In this work the complex resistance (Ω), a property of the particular component being measured, of a number of mortar cubes was measured using an impedance analyser. These resistance measurements were converted into resistivity ($\Omega \cdot m$), anintrinsic property of a type of material, using the physical measurements of the mortar cubes.

2. Research significance

In order to make an informed decision when producing conductive concrete, it will be necessary to understand the effect that choice and quantity of carbonaceous material as well as other parameters of the mix design will have on the electrical properties of the mix. This comparison of the effects of parameters of a conductive mix design on its complex resistivity will be useful for the production of conductive mortars and concretes for the applications mentioned in section 1.

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3. Materials, methods and equipment

3.1. Materials

The aim of this research was to investigate how mortar resistivity changes with the presence of a carbonaceous material (CBM) addition whose only purpose was to reduce resistivity magnitude. Two other factors common to all mortar mixes - relative quantities of different aggregates, and water to cement ratio - were also considered. No plasticisers were used.

A Portland fly ash cement, CEM II/B-V 32.5 N conforming to BS EN 197-1, was used for all mortars. Two natural fine aggregates conforming to BS EN 12620 of differing particle size distribution were used to assess the effect of fineness of fine aggregate. The grading of both fine aggregates is shown in Figure 1. The finer of the two aggregates was an alluvial sand (s), whilst the coarser fine aggregate was a Marlborough grit (g). The two fine aggregates were combined in g/s ratios of 0.6 to 1.2. This represents a change in fineness (expressed as percentage passing the 50 μm sieve) of 36.5% to 50% by mass. Grading of the aggregates is given in Figure 1:

The CBMs selected were: milled carbon fibre powder (CFP) and graphite powder (GP). The CFP was typically greater than 5 μm in length and less than 3 μm in diameter. The particle density was approximately 1800 kg/m^3. The particle size of the GP was such that 85% passed a 44 μm sieve. The particle density was approximately 1900 kg/m^3.

Details of the 24 mixes used are given by Table 1.

3.2. Preparation of mortar specimens

A series of 24 mortar mixes were produced. Ratios of the different fine aggregates were intended to correspond to the range of fine aggregate finenesses used in concrete. Water to cement ratios were chosen largely for practical reasons, with a high water content used to facilitate mixing. The sand to cement ratio ranged from 3 to 3.4 in all mixes and the w/c ratio ranged from 0.7 to 0.9 for the non-conductive mortars and from 0.9 to 1.2 for mortars containing CBM. Higher w/c ratios were used for the CBM mortars because it was found that this was necessary to maintain consistence and properly mix the materials. Whilst it may have been possible to use lower w/c ratios by use of water-reducing admixtures, as will be likely when conductive concrete is produced for practical applications, this would have increased the complexity of the mixes and may have obfuscated the effect of w/c on conductivity in this parametric study.

CBM was added to the mortars in proportions of 1 to 9% by mass of mortar; which represents approximately 5 to 32% by mass of cement + CBM.

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Mixing was carried out by hand. Prismatic specimens of 40 x 40 x 48mm were cast for each mix. Slight variations in length were allowed and accounted for in electrical property calculations. Fine aggregates and cement were mixed together before the addition of water. The manner in which the CBM was added differed when using CFP or GP. CFP preliminary mixes with relatively low WPCM showed that initially dispersing the CFP in water was a viable way of reducing some of the safety risks associated with the powder. When making the higher WPCM mixes this practise was found to lead to flocculation of the powder and extra physical mixing had to be done to mitigate this effect. In contrast the GP was found to float in the water, so was added directly with the fine aggregates and cement, with the safety risks being addressed with personal protective equipment.

The specimens were placed in a controlled environment room ($20^\circ C$, 40% RH) for 24 hours. All specimens were demoulded at 24 hours and stored in water at $20^\circ C$ until an age of 35 days.

3.3. Electrical measurements

Measurements were taken using an Agilent E4990A impedance analyser. Each mortar cube was removed from the water and surface dried using a cloth before measurements were taken. Surface temperature was not controlled when out of the water. These temperatures were not used in the analysis but are included in the online data for the study.

Measurements were taken at 7, 14, 21, 28, and 35 days after casting the mortar. Stainless steel electrodes were clamped to the cubes and connected to the impedance analyser using the four-terminal pair probe configuration described by Agilent Technologiessection 3.1.4, as shown in Figure 2.

The initial set of measurements was taken at 200 frequencies within the 20Hz-20MHz range, using a linear frequency sweep. For subsequent measurements the scheme was changed to use 1000 frequencies in a logarithmic sweep to better represent the response atlower frequencies. Measurements above 10MHz were found to be significantly affected by the measurement probes in use. These were discarded.

Some particular combinations of mixes and times have not been presented in this paper where they are not pertinent to comparisons being made, but all of the data produced for the research is available online - see the data access statement for details.

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4. Results and discussion

Comparisons of measurements showing the impact of three factors on the resistivity of mortar are presented. Nyquist plots show the frequency response for some mixes, as well as graphs and tables showing variation in individual frequency resistivity values. Results are separated between those pertinent to electrical properties at 35 days, and during the hydration process.

4.1. Conventional mortar results

This section deals with the complex resistivity of non-carbonaceous mortar in order to provide a baseline. As the mixes were not typical of industrial mortars, and did not contain some of the materials used in commercial contexts, they cannot necessarily be taken as representative of all mortar. However they are useful as a comparison with the conductive mortars.

The complex resistivity of non-carbonaceous mortar has been studied by McCarter (1994) and others. Figure 4 shows the frequency response for mix 1, which exhibits behaviour consistent with that previously reported for mortar. This response consists of an electrode arc, dominated by electrode contact effects, up to a frequency of around 10KHz. Above this frequency the bulk arc is observed, which is the result of capacitive behaviour of the mortar matrix.

4.1.1. Mix properties of conventional mortar and resistivity at 35 days hydration

Figure 3 shows resistivity values for non-carbonaceous mixes at 35 days after casting. Mix 2 (w/c=0.8, g/s=0.8) also fits between mixes 4 and 5 when considering the effects of grit and sand.

Figure 4 shows a Nyquist plot for mix 1 taken at 35 days after the initial casting. This was a typical response for mortar, showing a clearly defined bulk and electrode arc. Figures 5 and 6 show the frequency responses for the non-carbonaceous mortar mixes taken at 35 days after casting. Different markers show order of magnitude increases in frequency, from 20Hz to 10MHz - the same markers are used in all following Nyquist plots, and measurements at these order of magnitude frequencies are used to compare mixes.

Varying the ratio of grit to sand in the mortar from 0.6 to 1.2, as shown in Figures 3 and 6 changed the final $|Z|\cdot \mathrm{m}$ by an average of 2.9% and a range of 3.0 percentage points over the order of magnitude change frequencies with the largest change, -4.1%, occurring at 1KHz. For the phase shift the average was -1.2% with a much larger range of 11.7 percentage points.

For comparison, changing the water to cement ratio from 0.7 to 0.9, also shown in Figure 3 as well as Figure 5 produced an average $\Delta|Z|\cdot \mathrm{m}$ of -29.2% and an average change in phase shift of -10.7%. This relatively small number of data points suggests that changes to the water to cement ratio have a more significant effect on the resistivity of mortar than altering the proportions of non-conducting aggregate components.

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4.1.2. Mix properties of conventional mortar and resistivity from 7 to 35 days age

Figure 7 shows the percentage change between measurements taken at day 7 and day 35. Fewer spot frequencies were used in the 7 day measurements than in subsequent sets. The results show that the resistivity generally increased overthe course of the hydration process, although mixes 1 and 5 showed a small reduction in resistivity at low frequency. Changes to the phase angle over the hydration process were small.

Forde *et al*. (1981) found that the resistivity of conventional concrete and cement paste increased exponentially until around 20 days of curing, and then continued to increase linearly at a gradual rate thereafter. This study did not assess whether or not the resistivity change until 20 days was exponential.

There was a general trend towards an increase in resistivity magnitude over time, especially at higher frequencies, as observed in mixes 1 to 6. This behaviour was not always observed, and in some cases the day 21 resistivity magnitude was the highest measured, with the other data exhibiting the expected behaviour. This does not correlate with the variations in temperature measured on the cubes during testing, and may instead be the result of variation in clamping pressure on the electrodes.

4.2. Complex resistivity of conductive mortar at 35 days

The conductive mortar mixes were the main focus of the study. This section deals with the resistivity of the conductive mortar mixes at 35 days of hydration.

Two aspects of the results are considered here: (i) the effects of different mix parameters on resistivity magnitude and shape of the frequency response in conductive mortars, and (ii) differences between the two conductive additions used. Since the differences between GP and CFP were found to be relatively similar in effects (see section 2) and GP appears slightly more often in the literature, it is presented as the “baseline” addition.

4.2.1. Effects of changes in WPCM, g/s, and w/c on complex resistivity

Figure 8 shows resistivity values for mixes with varying WPCM, measured 35 days after casting. The results consist of a general decrease in resistivity magnitude as WPCM was increased, for all frequencies. Resistivity magnitude for each mix decreased as frequency was increased in all cases. At frequencies below 10KHz the resistivity was actually increased between 1% and 3% WPCM, and at frequencies below 1KHz the same behaviour was observed between 1% and 5% WPCM.

After around 35 days of hydration previous work has shown that there is little further change to the mortar resistivity (Forde *et al*., 1981). Measurements from this stage were used to compare the effects of variation in the other mix parameters in conventional and conductive mixes.

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Table 2 shows the change in measured complex resistivity caused by the maximum changes to each mix parameter. The maximum differences in w/c and g/s in the conventional mortars and WPCM in the GP mortars are presented. The changes have been averaged over the order of magnitude frequencies to compare the overall effect of each factor. W/c and g/s are compared in the conventional mortar mixes, and WPCM is compared using mortars containing graphite powder.
Figure 9 shows the development of the frequency response across mix 3 and mixes 16 to 19, representing content of GP from 0% to 9% by mass, with less variation in other variables. In contrast, Figure 10 showsthe variation when the CFP content was kept at 4% by mass while other parameters were altered. The two graphs show stronger variation in $\Omega \cdot \mathrm{m}$ as a result of changes to WPCM than other parameters.

Figure 9 shows the effect of varying WPCM on resistivity for the mortars containing graphite powder. For comparison Figure 5 shows variation in w/c, and Figure 6 shows variation in quantities of grit and fine sand in non-conductive mortars. Table 2 is presented to give a condensed idea of the change caused by each of the variables tested in the study.

The change from w/c = 0.7 to w/c = 0.9 produced a change from $93.1\,\Omega \cdot \mathrm{m}$ to $58.6\,\Omega \cdot \mathrm{m}$ at 10KHz. Figure 6 shows an unexpected effect of changes to g/s, where g/s = 0.6 and g/s = 1.2 were relatively close togetherand g/s = 0.8 had a somewhat differently shaped frequency response. This may be due to differences in the distribution of the grades of sand. If the results are taken to be representative, the largest change in resistivity magnitude at 10KHz was between g/s = 0.8 at $66.5\,\Omega \cdot \mathrm{m}$ and g/s = 1.2 at $50.1\,\Omega \cdot \mathrm{m}$.

Water to cement ratio was varied from 1.0 to 1.2 (mixes 9 and 12) with a constant mass of CFP, and from 0.9 to 1.0 (mixes 18 and 21) with a constant mass of GP. In both cases the variation in measured resistivity was relatively small. Between mixes 9 and 12 the resistivity changed by an average of $-3.3\,\Omega \cdot \mathrm{m}$ with a phase change difference of 2.4°. The difference was smaller between mixes 18 and 21, which follows from the smaller change in w/c. For this case the resistivity changed by an average of $1.0\,\Omega \cdot \mathrm{m}$ with a phase change difference of 0.06°. An increase of 0.2 in the w/c of the conventional mortars led to an average change of $27.7\,\Omega \cdot \mathrm{m}$ and 1.3°.

Varying the grit to sand ratio from 0.6 to 1.2 in mixes containing 5% CFP by mass (mixes 13 and 15) led to an average resistivity magnitude change of $0.03\,\Omega \cdot \mathrm{m}$ and phase shift difference of 1.7°. This average change in resistivity magnitude represented 1.2% of the $|Z| \cdot \mathrm{m}$ for mix 13. For the same change in the GP case, the average change in resistivity was $15.8\,\Omega \cdot \mathrm{m}$, with a phase shift difference of 5.6°. For comparison, the average difference in resistivity from the g/s variations in the conventional mixes was $1.7\,\Omega \cdot \mathrm{m}$.

Figures 5 and 6 show the changes made to the frequency response by altering the ratios of water to cement and grit aggregate to sand in mixes with no CBMs. Figure 10 shows the effects ofsimilar alterations when CBM quantity was held at 4%. Changes to w/c and g/s have very little effect on the shape of the complex resistivity frequency response of the mortar. In the non-conductive mortars this is shown by Figures 5 and 6, in which the basic electrode arc/bulk arc shape was maintained consistently in spite of changes to resistivity magnitude. In contrast, Figure 9 shows a large change in the shape of the Nyquist plot as WPCM was

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increased. The electrode and bulk arcs became less distinct until the response shape consisted of a single arc, ending in a region characterised by an increase to imaginary resistivity with very little change to real resistivity. Figure 10 shows that changes to w/c and g/s had a similarly small effect on the shape of the Nyquist plot in mixes with a conductive addition.

Table 2 shows that at 35 days hydration the 3% WPCM graphite powder mix (mix 17) had a larger mean resistivity magnitude than the 1% mix (mix 16). Figure 11 shows this in more detail, and Figure 12 shows similar effects in the carbon fibre powder mixes. In the GP case the 1% WPCM mix had an unexpectedly low resistivity magnitude below 10kHz, and in the CFP case the same was true below 1kHz. In both cases the progression from 3% WPCM onwards was as expected i.e. a reduction in resistivity magnitude at all frequencies. The unexpected behaviour of the 1% WPCM mix may have been due to differences in the distribution of the additions within the individual mortar cubes or due to some effect of the additions on the hydration process.

Alterations made to the g/s and w/c parameters of conductive mortar have a small effect on the resistivity of the mortar, when compared to changes to the WPCM or to changes to those same parameters in conventional mortar. The practical result of this is that when considering the complex resistivity of a conductive mortar designed using carbonaceous materials, the addition is the primary concern. Further work is needed to determine if materials such as plasticisers have an effect closer in scale to that ofthe carbon powders than w/c and g/s.

4.2.2. Comparison of graphite and carbon fibre additions

Figure 11 shows resistivity magnitude against frequency for different weight percentage of graphite powder. Figure 12 shows the same for carbon fibre powder.

Figure 13 shows the Nyquist plots for mixes 3 and 7 to 10, representing CFP content of 0% to 9% by mass. Figures 9 and 13 can be used to compare the difference in effects on Nyquist plot shape between the two types of addition.

Figures 11 and 12 present $|Z|\cdot \mathrm{m}$ at order of magnitude change frequencies for different weight percentages of GP and CFP, while Figure 8 gives the complex resistivity including phase shift of thegraphite powder filled cubes measured at 35 days.

The results for the graphite and carbon fibre powders were generally relatively close for the same WPCM, though this varied depending on frequency. The 9% WPCM case was the closest, with an average difference of $1.5\,\Omega\cdot\mathrm{m}$ across the order of magnitude frequencies. It should be noted that this still represented a significant percentage difference because of the overall low resistivity at this WPCM. The most significant difference was in the 1% case at 20Hz, in which the CFP mortar had a smaller resistivity magnitude by $25.7\,\Omega\cdot\mathrm{m}$, corresponding to 49.5% of the GP resistivity magnitude for that frequency. Other than this there was only one other case (WPCM of 1% at 100Hz) of an absolute difference of more than $10\,\Omega\cdot\mathrm{m}$. Differences in phase shift were also relatively small, with the largest being 12°.

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The differences in spot measurements between the GP and CFP were of similar magnitude to those resulting from changes to g/s and smaller than those for changes made to w/c. It is also important to consider that the two CBMs were mixed differently, and this may account for some of the difference in resistivity.

A comparison of Figures 9 and 13 shows the difference in the shape of the frequency response of the two types of conductive mortar. The effect of increasing WPCM was very similar in both cases. Each of these sets of responses was dominated by the carbonaceous material, as evidenced by the very minor effects of the changes to the other parameters. It is therefore reasonable to expect that the differences in shape of frequency response reflected either differencesin the frequency response between the two materials, or differences in the distribution of particles within the mortar matrix.

4.3. Conductive mortar over the hydration process

Time development of the resistivity of mortar is related to the hydration process. It has therefore been studied for use as an indicator of the mechanical properties of a mortar at a particular point in time. This section compares the time development of $\Omega \cdot \mathrm{m}$ in mortar with and without carbonaceous materials.

Figure 14 shows the complex resistivity of a non-CBM mortar (mix 1) generally increasing over the hydration process.

Figure 15 shows the resistivity of a 9% WPCM GP mortar (mix 19) over the hydration process.

Figure 16 gives an indication of the effect of the addition of carbonaceous materials on the time dependence of the resistivity of mortar.

Figure 14 shows that the resistivity of the shown non-CBM mortar increased over time, which is consistent with previous findings (Forde *et al*., 1981). In the CBM infused mortar the change in resistivity over time, as shown for a high-CBM case by Figure 16, would be expected to be less significant than than the standard mortar, because the CBMs which dominate the conduction behaviour are not believed to be affected by the chemical processes associated with curing.

Figures 14 and 15 show that neither mix 1 nor mix 19 underwent substantial change to the shapes of their Nyquist plots during hydration. However it is immediately clear that the change in $\Omega \cdot \mathrm{m}$ was much less significant in the high-CBM case than the non-CBM case. Use of electrical properties to indicate progress in the hydration process can therefore be expected to be much more difficult in a conductive mortar than a conventional one. However, small variations of complex resistivity with hydration stage were observed even at the highest WPCM, especially at low frequency as shown in Figure 16. It is possible that there remains scope for correlating resistivity with hydration stage given sufficiently sensitive equipment.

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4.4. Mortars and concrete

This study has assessed the resistivity of mortars for practical reasons. Therefore there is the question of how well this information could be applied to concrete. McCarter (1996) measured the resistivity of both cement pastes and concrete. The findings in that case were that in general mortars and concretes would respond to changes to the same parameters in similar ways. However the addition of the large aggregates made a significant difference to not just the magnitude of resistivity but also to the characteristics and shape of the frequency response.

In spite of this, information on altering the electrical properties of mortar will inevitably be of some use for producing concrete. At lower AC frequencies or when applying DC, the mortar paste will provide the dominant conduction path. The interface between the concrete and any electrical measurement equipment will also primarily be comprised of mortar paste.

Use of conductive mortar pastes in concrete may also affect the durability of the concrete. Reduced resistivity may facilitate the flow of harmful ions such as chlorides and sulfates into the concrete body, causing reinforcement to deteriorate. Further research is necessary to determine whether the conductive mortar affects the appropriate usage cases of the concrete.

5. Conclusions

Complex resistivity data for mortars containing varying mix parameters including quantities of carbonaceous materials have been presented. From this data it is clear that changes to the quantity of carbonaceous material present had a greater effect on resistivity than these changes to the water or aggregate content of the mix. The general effect of a graphite powder addition has been found to be similar to that of carbon fibre powder. Though the difference between resistivity magnitudes when comparing mixes using the two additions was small, some differences in the shape of the frequency response were observed. If this shape difference can be ignored for a particular application, the decision on which option to choose can be made based on other factors than effect on complex resistivity. Separately from resistivity effects, both additions tested were found to increase the necessary water content of the mix in order to mix properly. Potential users should be aware of this when working with these conductive additions.

The range of g/s tested roughly reflected the extremes of what is practical. W/c values were high to facilitate mixing, but the range in ratios was similar to the range that would be found in practically useful mortars. The data shows that of the two other mix factors varied, changes over these ranges to the w/c ratio have a greater effect on resistivity than changes to aggregates. Neither factor caused any change to the shape of the frequency response. In a conductive mix the effects of changes to the other mix parameters on resistivity are reduced further compared to the non-conductive mixes. The presence of carbonaceous powders in the mortar reduced the effect of the hydration process on resistivity, even with relatively small quantities of powder. All of these outcomes are consistent with the dominant electrical conduction path shifting from the cement to the dispersed CBMs in the mortar. Overall the WPCM has been shown to be the most important factor for attempting to control the resistivity of a mortar. This has been demonstrated with two materials which are relatively

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affordable. The literature identifies other materials which are more effective at reducing resistivity, and therefore very likely to render other factors of the mix even less important.

These results on mortar will also be of interest to those investigating controlling the electrical properties of concrete. Further work is perhaps needed to understand the effects of conductive mortar on the complex resistivity characteristics of concrete. Further work is also necessary to assess the way a conductive mortar may affect the durability of concrete, especially in regards to reinforcement.

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Data access statement

Data collected during this study is freely available at https://doi.org/10.15125/BATH-00434 Where more data has been collected than used, this is made clear and justified in the article text.

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Table 1. Table of mixes tested

Mix ID	CBM	WPCM	g/s	Mass ratios relative to cement			
				w/c	**s/c**	**g/c**	**CBM/c**
1	None	0	0.8	0.70	1.67	1.33	0.00
2	None	0	0.8	0.80	1.78	1.42	0.00
3	None	0	0.8	0.90	1.89	1.51	0.00
4	None	0	0.6	0.80	2.00	1.20	0.00
5	None	0	1	0.80	1.60	1.60	0.00
6	None	0	1.2	0.80	1.45	1.75	0.00
7	CFP	1	0.8	0.90	1.73	1.42	0.05
8	CFP	3	0.8	0.90	1.63	1.42	0.14
9	CFP	5	0.8	0.98	1.54	1.42	0.24
10	CFP	9	0.8	1.06	1.30	1.42	0.48
11	CFP	4	0.8	1.04	1.44	1.33	0.22
12	CFP	5	0.8	1.17	1.63	1.51	0.26
13	CFP	4	0.6	1.14	1.76	1.20	0.24
14	CFP	5	1	1.11	1.36	1.60	0.24
15	CFP	5	1.2	1.08	1.21	1.75	0.24
16	GP	1	0.8	0.90	1.73	1.42	0.05
17	GP	3	0.8	0.90	1.63	1.42	0.14
18	GP	5	0.8	0.90	1.54	1.42	0.24
19	GP	9	0.8	1.14	1.30	1.42	0.48
20	GP	5	0.8	0.95	1.44	1.33	0.22
21	GP	5	0.8	1.00	1.63	1.51	0.26
22	GP	4	0.6	1.16	1.76	1.20	0.24
23	GP	5	1	0.90	1.36	1.60	0.24
24	GP	5	1.2	1.08	1.21	1.75	0.24

Table 2. Differences in complex resistivity over parameter changes, averaged over order of magnitude frequencies

	w/c = 0.9 to 1.1	**g/s = 0.6 to 1.2**	**WPCM = 0 to 1**
$\Delta\lvert Z\rvert\cdot\mathrm{m}$	–27.72	1.73	–32.65
$\Delta\theta^{\circ}$	1.28	0.16	3.62

	WPCM = 0 to 3	WPCM = 0 to 5	WPCM = 0 to 9
$\Delta\lvert Z\rvert\cdot\mathrm{m}$	–27.45	–40.40	–57.48
$\Delta\theta^{\circ}$	–3.13	–2.15	8.90

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Figure captions

Figure 1. Particle size distribution of the fine aggregates.

Figure 2. Mortar cubes as clamped and connected to measurement equipment

Figure 3. Resistivity of non-carbonaceous mixes at 35 days after casting

Figure 4. Nyquist plot for mix 1: g/s = 0.8 w/c = 0.7 WPCM = 0. Markers indicate order of magnitude change for frequency.

Figure 5. Nyquist plot showing the effect of varying w/c ratio on complex resistivity at 35 days

Figure 6. Nyquist plot showing the effect of varying g/s ratio on complex resistivity at 35 days

Figure 7. Change in complex resistivity at 7 and 35 days after casting, for mixes 1, 3 and 5

Figure 8. Complex resistivity of Graphite Powder mixes at 35 days after casting

Figure 9. Nyquist plot showing the effect of varying GP content at 35 days

Figure 10. Nyquist plot showing the effects of varying w/c and g/s with constant 4% GP content at 35 days

Figure 11. Stimulation frequency vs. resistivity magnitude for different weight-percentages of GP at 35 days.

Figure 12. Stimulation frequency vs. resistivity magnitude for different weight-percentages of CFP at 35 days.

Figure 13. Nyquist plot showing the effect of varying CFP content at 35 days

Figure 14. Nyquist plot showing effects of age on complex resistivity for a mix without conductive additions

Figure 15. Nyquist plot showing effects of age on complex resistivity for a mix with 9% GP by mass

Figure 16. Δ % between complex resistivity measurements on mixes 16, 17, 18 and 19 taken at 7 and 35 days after casting.

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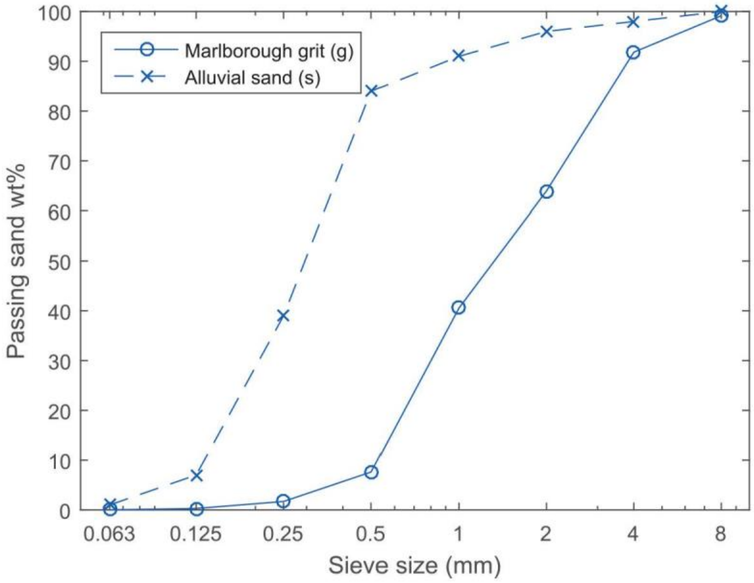

figure1_sand_grading

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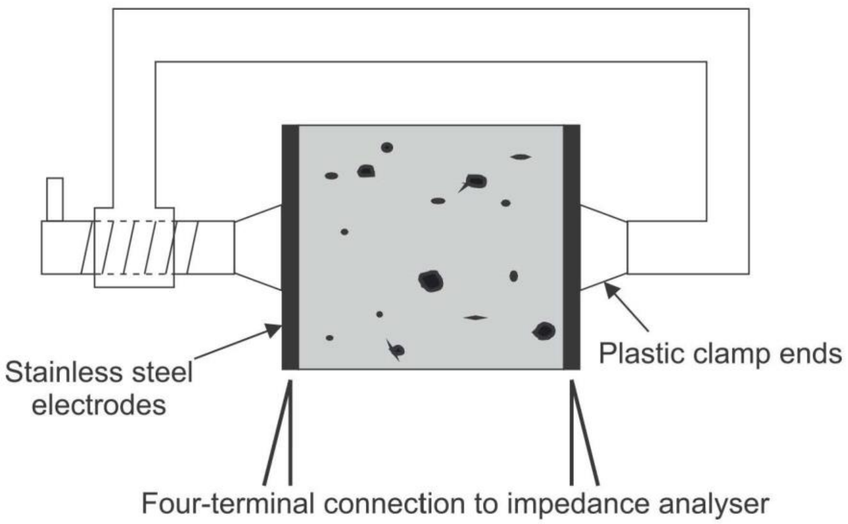

figure2-expt_meas_diagram

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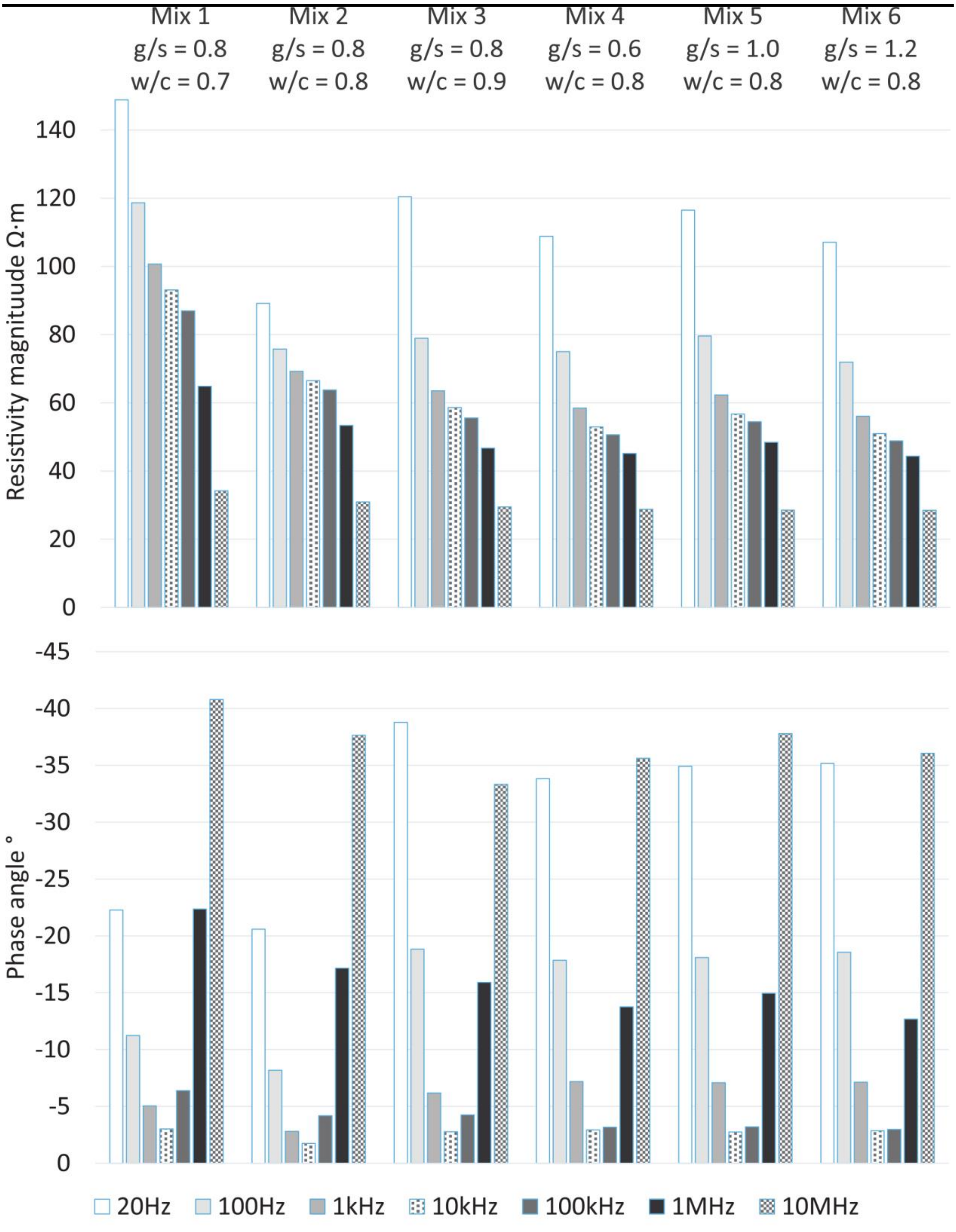

figure3-bar-noncbm-35days

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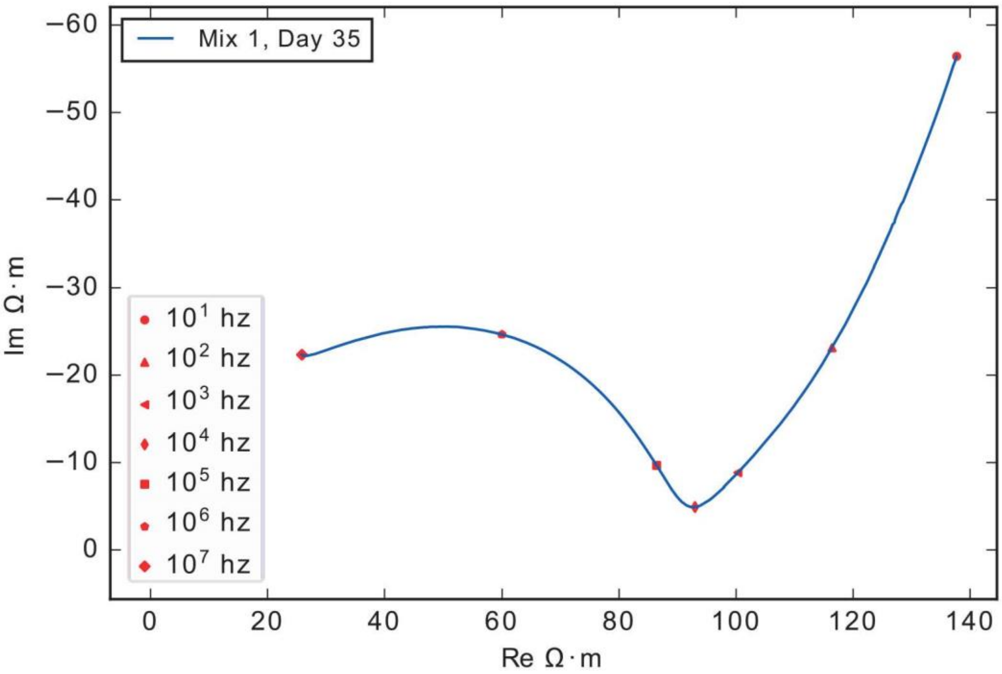

figure4-nyquist-mix1-35days-withlegend

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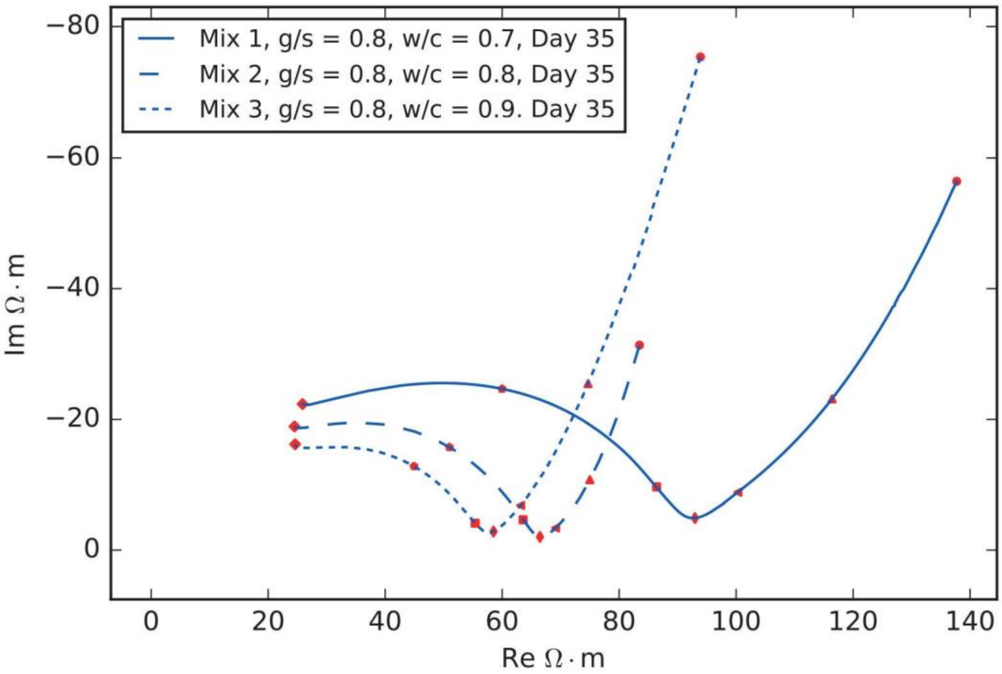

figure5-nyquist-1to3

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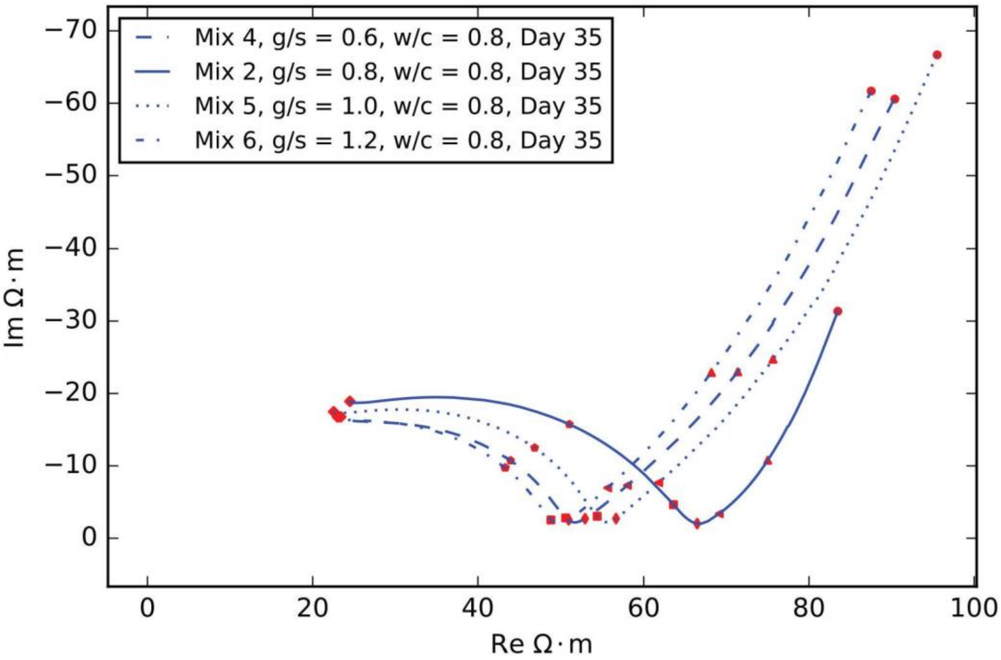

figure6-nyquist-2and4to6

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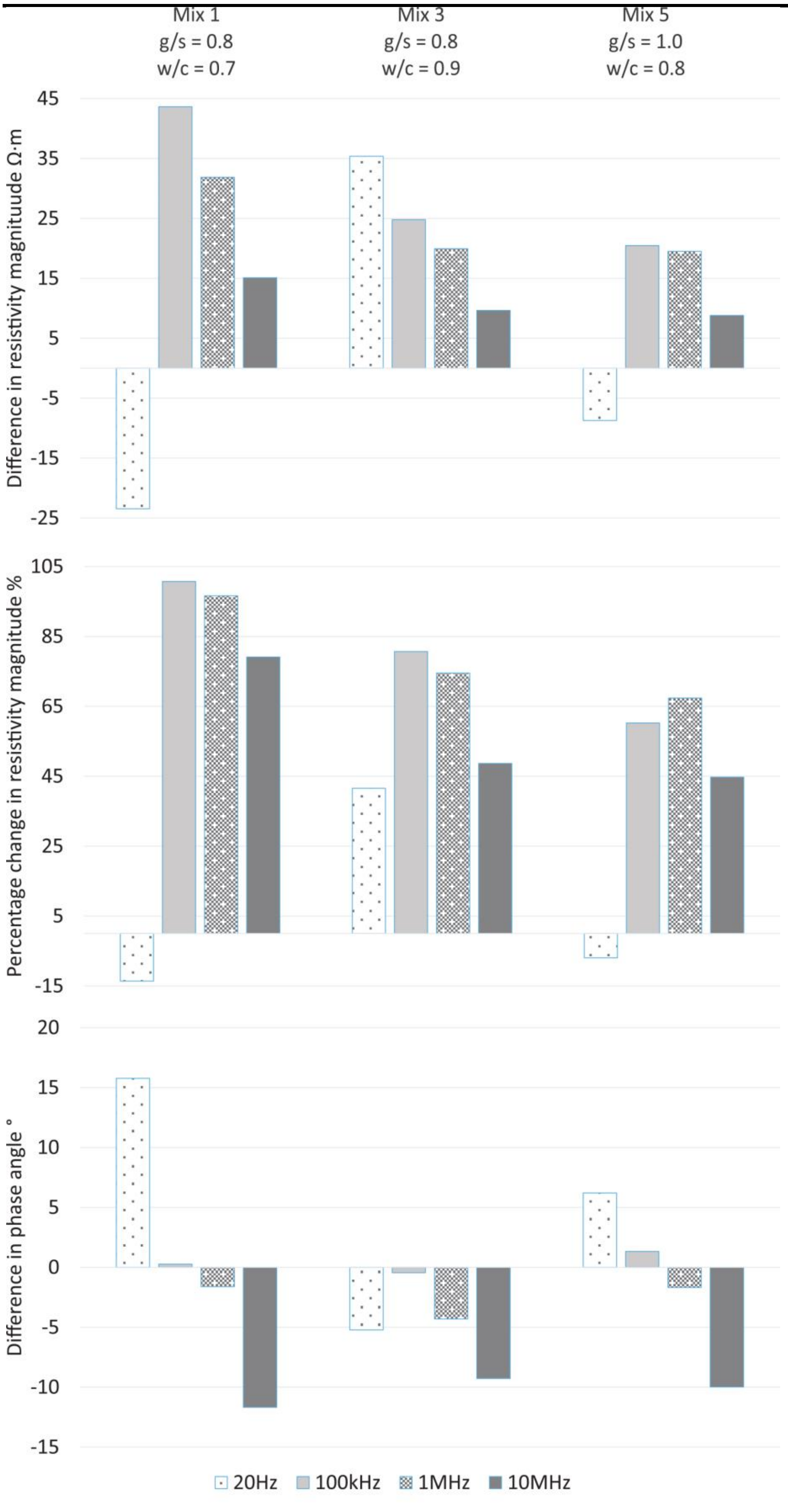

figure7-bar-mix135-time

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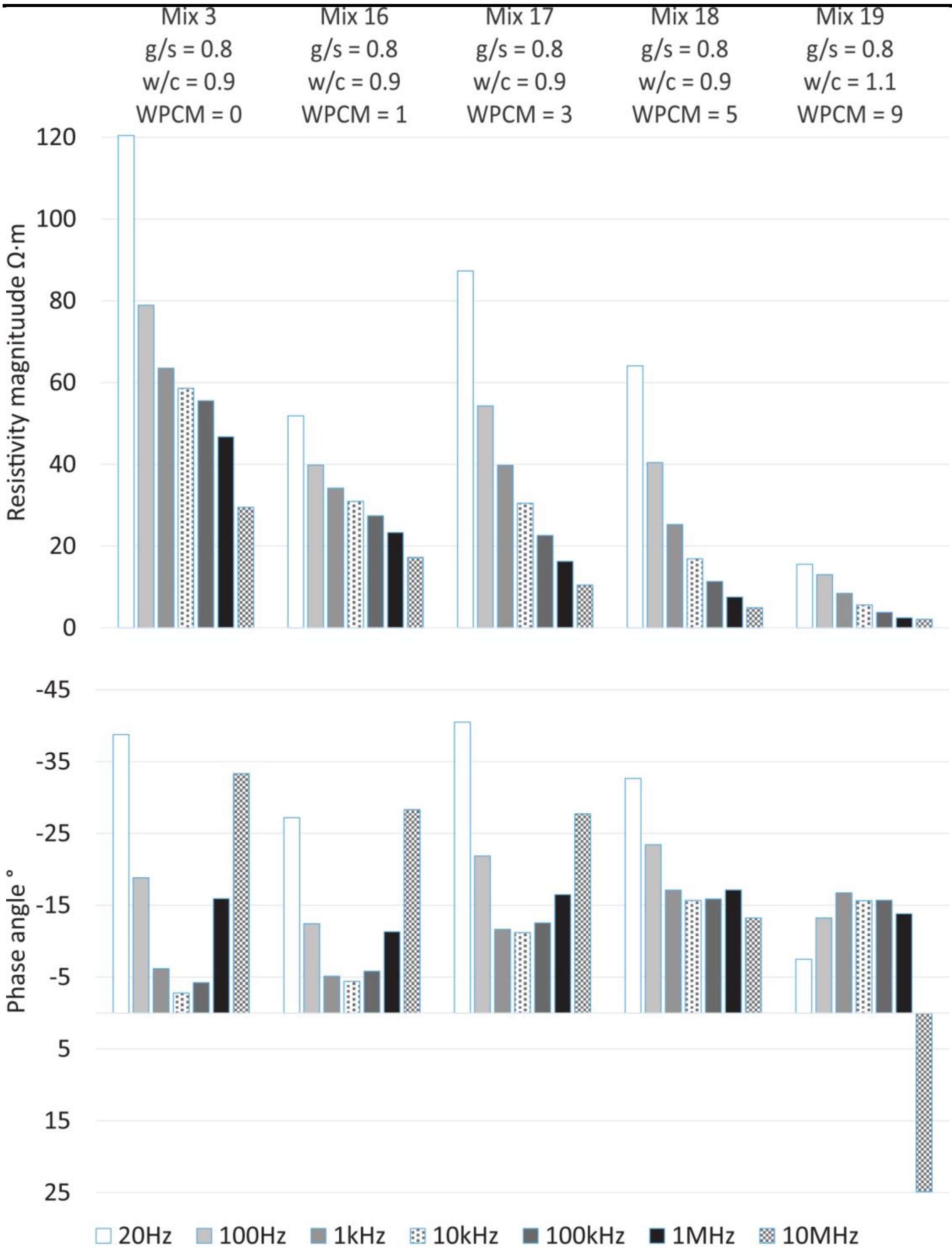

figure8-bar-GP-35days

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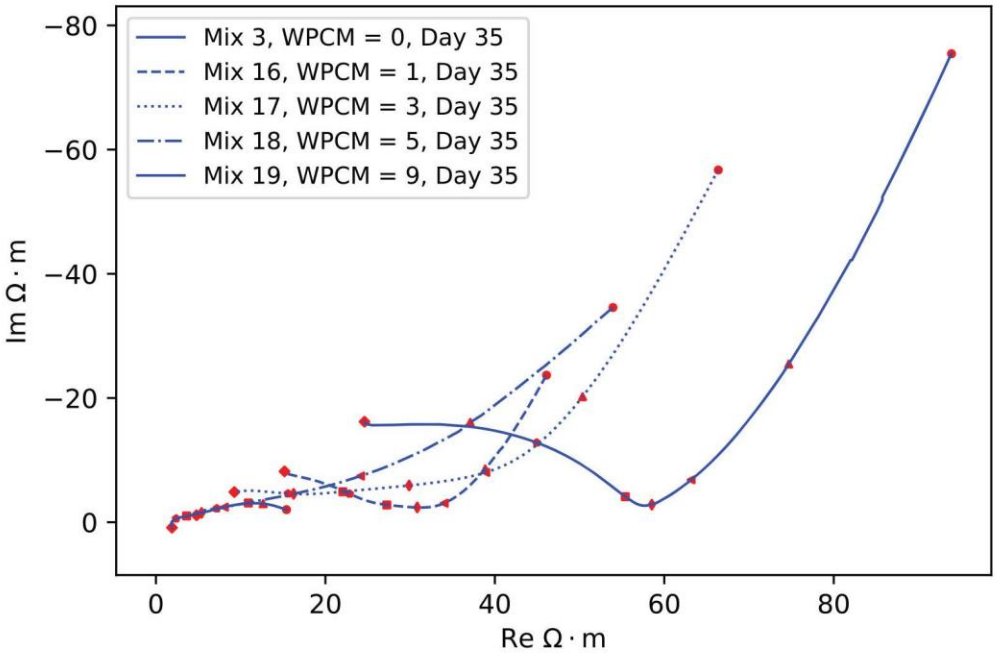

figure9-nyquist-3and16to19

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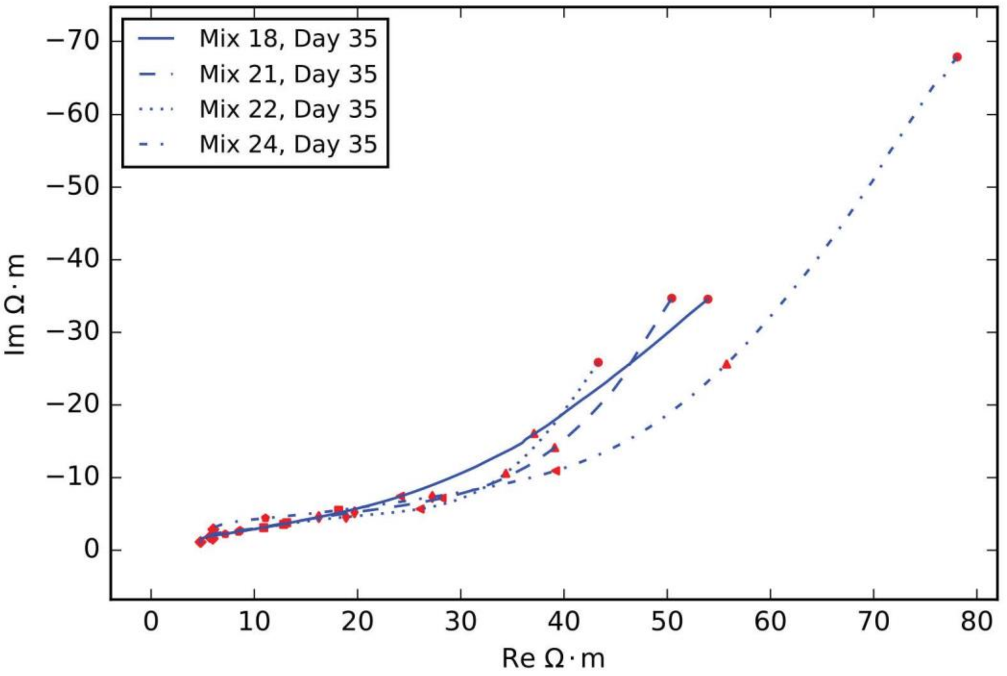

figure10-nyquist-18-21-22-24

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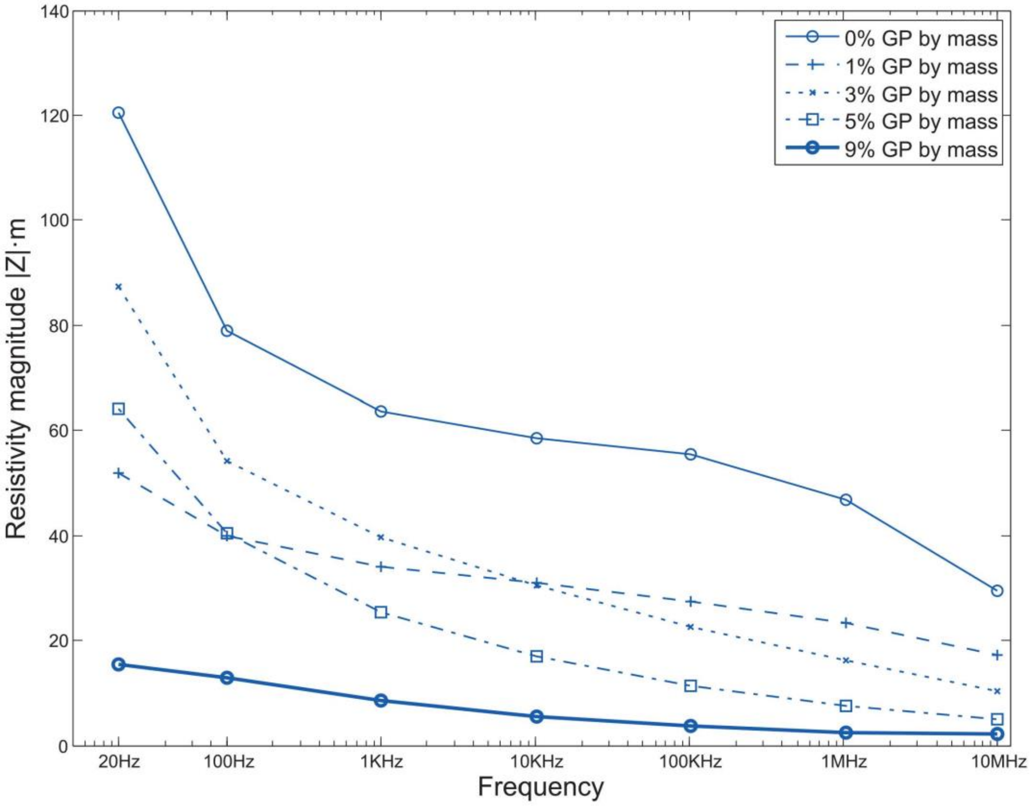

figure11-GP-final-by-percent

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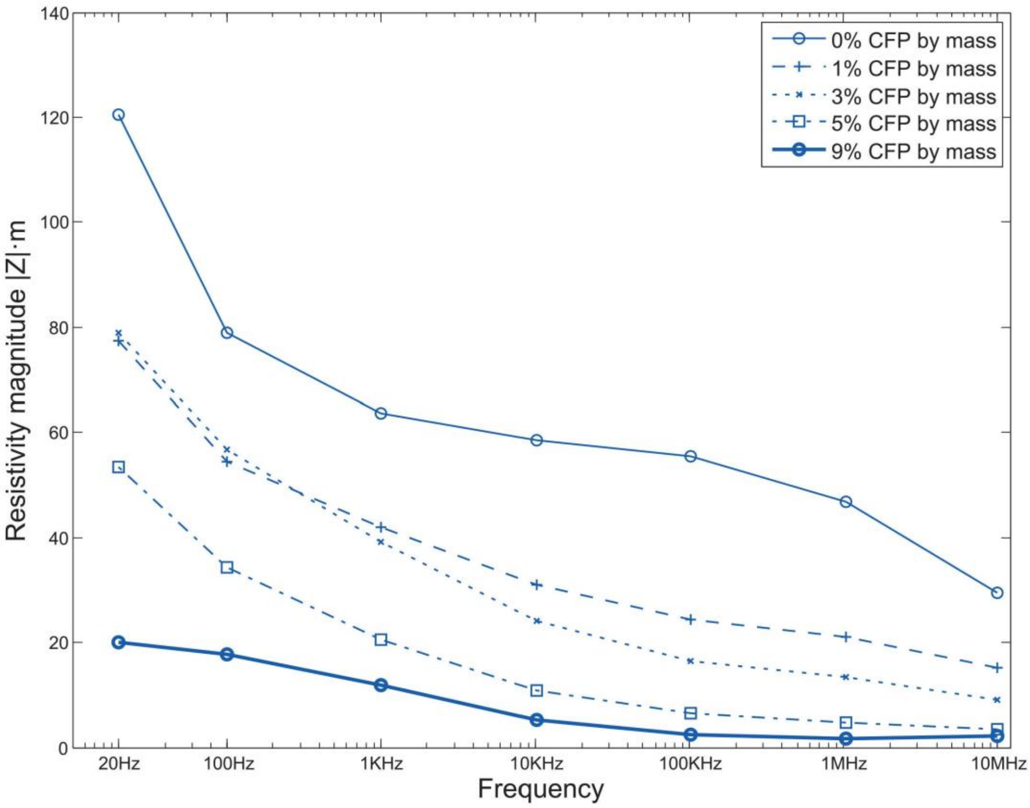

figure12-CFP-final-by-percent

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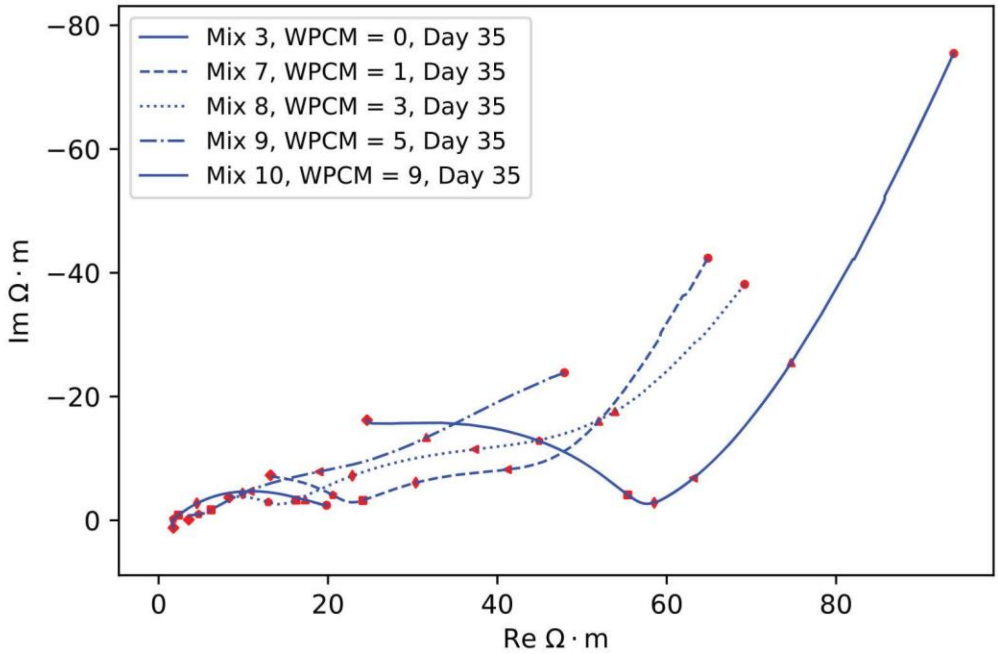

figure13-nyquist-3and7to10

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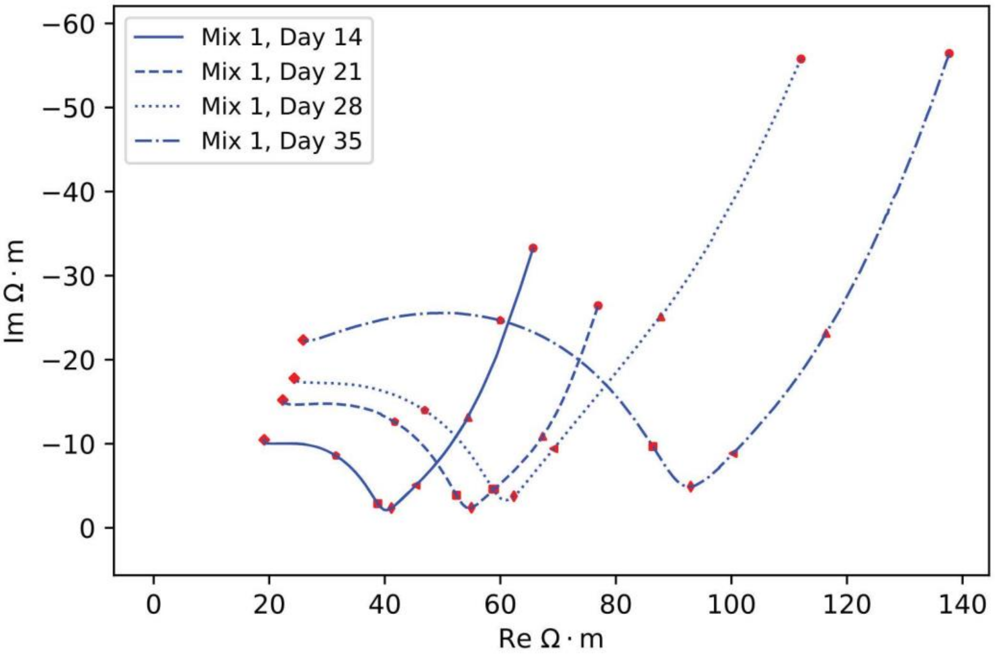

figure14-nyquist-mix1-time

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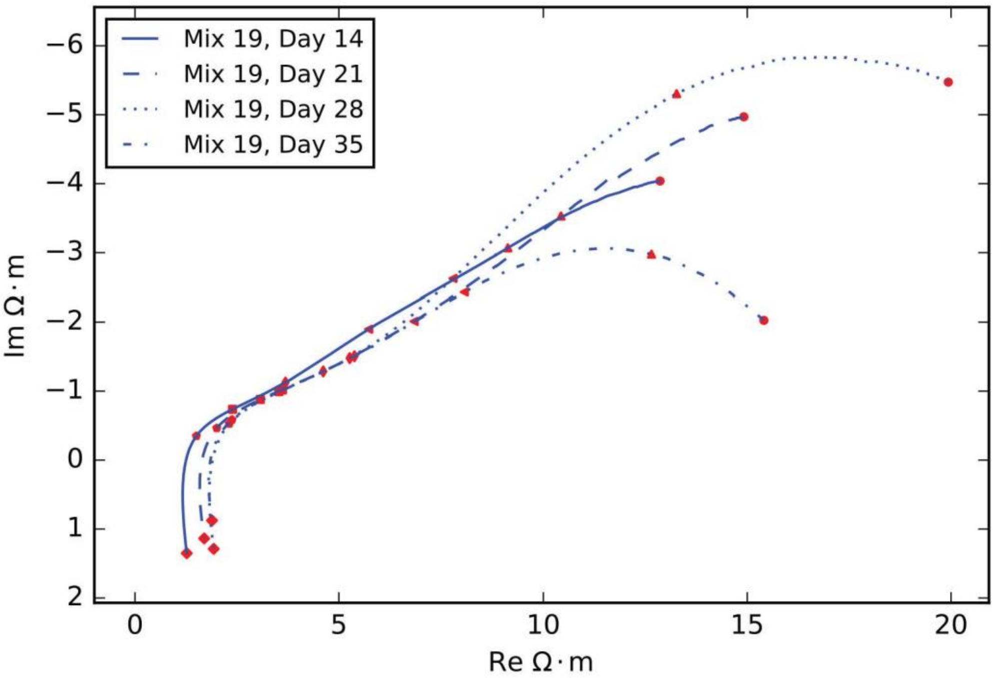

figure15-nyquist-mix19-time

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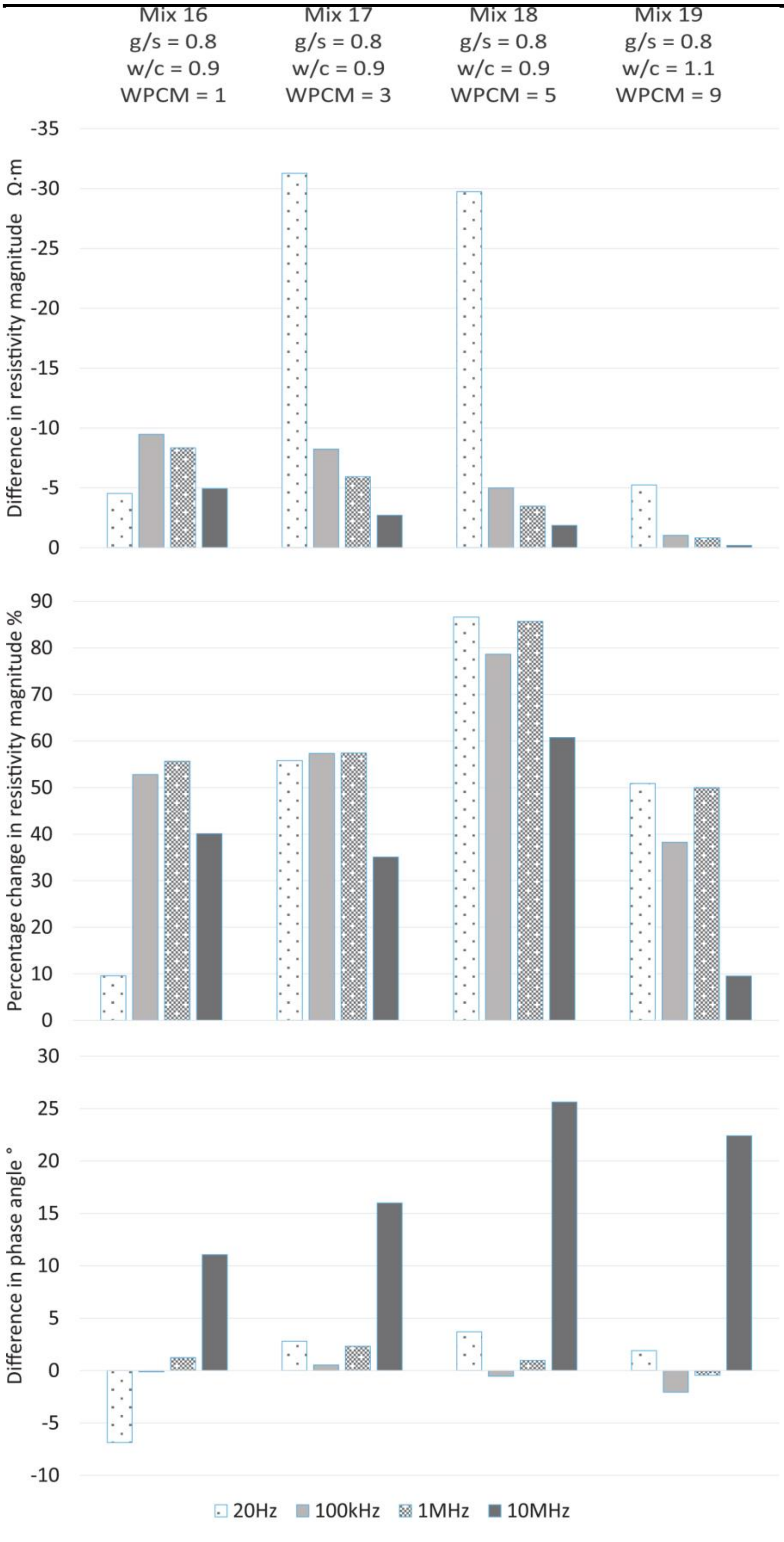

figure16-bar-GP-time

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